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Polymer-based nanocomposites as defence material

KARTIKEY SINGH[1,2], RIMPA JAISWAL[1,3], RAKESH KUMAR[1], SUBHAM SINGH[1] and KAVITA AGARWAL[1,*]

[1]DRDO Defence Material and Stores Research and Development Establishment, Kanpur 208013, India
[2]Department of Chemistry, Wayne State University, Detroit 48202, USA
[3]Bhabha Atomic Research Centre, Mumbai 400 085, India
*Author for correspondence (kavita.agarwal2005@gmail.com)

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Abstract. Nanotechnology has opened the doors for various novel defence applications, such as smart materials, novel fuel sources, energy storage devices, harder/lighter platforms and newer medical applications. Uses of composites instead of steel allow the possible assembling of lightweight aircraft, consequently reducing fuel consumption, CO_2 emissions and fuel costs. Because of their enhanced mechanical, electrical and thermal properties, these polymer nanocomposites and materials have been found in several defence-related areas, such as the military, automobile, electronics, food and leisure. This overview aims to provide insight into the rapidly developing capabilities of lightweight nanofiller-reinforced polymer nanocomposite materials and explore their potential uses in various defence-related applications.

Keywords. Nanocomposites; polymer-based nanocomposites; nanotechnology; defence materials.

1. Introduction

Nanotechnology promises innovative technological variations for a broader range of applications in defence sectors. These sectors include mobility, sensing, stealth, aerodynamics, management, power generation, smart structural materials, robustness and resilience [1]. Nanotechnologies influence battlespace systems concerned with signal processing and information, intelligence and autonomy. Information technology is anticipated to acquire substantial advantages from emerging capabilities such as novel electronic displays, threat detection and interface systems [2]. Additionally, they will have a significant role in developing robotics and miniaturized unmanned autonomous vehicles (UAVs) [3].

The design and development of materials based on nanotechnology provide new structural characteristics material, which possesses better performances, such as lessening in upkeep (reducing wear, facilitating self-healing and repair), ease of tenability (engineering materials) and new types of electronic/optoelectronic/thermal/magnetic properties [4].

Nanocomposite is a fascinating science and technology area that emerged in the 1980s at Toyota Research Laboratory in Japan. The initial interest in this field is focused on basic research concerning the potential use of plenteous literature on nanocomposites manufacturing and characterization [5, 6]. The past decades have witnessed a steep growth in smart polymer and elastomer developments reinforced with magnetically polarizable elements like iron [7]. Ferromagnetic or superparamagnetic polymer composites have applications for dynamic vibration-damping materials, conductive seals, gaskets in missiles, magneto-rheological elastomers, magnetic recording media and flexible magnetic devices [8–13]. Fe_2O_3 nanoparticles-reinforced conducting polymer (e.g., polyaniline) nanocomposites have been established to diminish dielectric and magnetic loss to attain the greatest absorption of electromagnetic energy [14]. Nanocomposites in aircraft construction induce the fortifying component for structures, such as stringers, frames or honeycomb-type forms used as the outer layer of the wings and fuselage. Carbon nanotube (CNT) and graphene-reinforced nanocomposites are thoroughly evaluated in ballistic protection and body armor [15]. Continuous research on nanocomposites for defence applications is ongoing, given electrostatic charge dissipation [16], shock-absorbing materials [17], electromagnetic shielding [18], fire retardation [19], solid lubricants [20, 21] and corrosion protection [22].

The nanocomposite field is rapidly growing, the primary and obvious incentive being the potential commercial use of these materials in civilian applications. The primary research is applied to the process of material development to achieve semi-finished or specific products. Automotive companies offer novel products in sports and consumer goods to consumers with improved quality and functioning of existing products through nanocomposite technology [23, 24].

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Nanocomposite technology will likely facilitate the development of many new products and materials in the upcoming years. This review attempts to present a rational representative cross-section of nanocomposite polymer and its applications for the defence sector, provide a qualitative overview of the field's development and progress of nanocomposite polymer, and explore defence applications.

2. Polymer nanocomposites

Nanocomposites define materials based on polymer, containing particles (equiaxed or elongated) or fibres in the dimension of 1–100 nm [25]. They may belong to either inorganic (ceramic or metal, including semiconductors) or organic (e.g., polymer) material and exclude metal–matrix nanocomposites and, similarly, ceramic–matrix nanocomposites and beyond the scope of the current discussion.

Reinforcing of polymers using inorganic or organic material fillers is a common practice in modern plastics production. Polymeric nanocomposites (PNCs) represent a radical alternative to conventional filled polymers or polymer blends. In traditional systems, the reinforcement is by order of microns while the PNCs are discrete constituents of a few nanometres (< 100 nm) in at least one dimension [26]. PNCs can be classified based on their shape, figure 1.

Nano-size fillers lead to an extensive interfacial area in the composites that controls the degree of interaction between the polymer and the filler and defines the properties. As in conventional composites, the interfacial region begins at the point in the fibre from where the properties differ from those of the bulk filler and end in the matrix to the point where properties become equal to those of the bulk matrix [27]. Polymer-based nanocomposites can be divided into three classes based on base polymer, filler inclusion and application (figure 2).

The comparisons were carried out between modified polymer-based nanocomposites and the currently used unchanged polymer matrix. The demerits that arise are the functional properties of ordinary composites, such as electrical, magnetic and optical, which can be changed by adding various particles as fillers but leads to a significant decline in the mechanical properties of the polymer [28]. On the other hand, the uniform introduction of nanofiller (carbon nanotubes (CNTs), graphene, silica, etc.) into the nanocomposites can lead to improved properties in multiple aspects, such as improvements in mechanical properties, improvements in thermal properties, improvements in the electrical properties, better fire resistance, numerous other benefit's, and improvements can be achieved such as in applications by using nanocomposites for optical and magnetic properties [29–32] (figure 3).

There are countless possibilities for employing polymer-based nanocomposites in the defence sector. Cost efficiency and lightweight are other areas that the benefits of nanocomposites reflect. The starting cost for new material to be cheaper and more economical is unusual than the one currently in use, simply because of the investment and processing equipment expenses. However, this can be avoided if the novel material can be processed and manufactured using the existing practice. Polymer nanocomposites might be where current operational technology can be optimized and applicable to new advanced materials.

3. Defence applications of nanotechnology

Development in the field of nanotechnology is applicable to the defence sector results in the advancement of various applications, including but not limited to: sensors, smart textiles and lightweight yet resilient materials for military weapons. The focused research areas for developing technologies for defence applications include nanocoating, nanomaterials and nano-manufacturing. Nanotechnology application makes an impact in the field of medicinal chemistry [33, 34] as targeted delivery with enhanced therapeutic parameters such as nanomedicine [35] and nanoformulation [36]. For cutting-edge chemical clusters

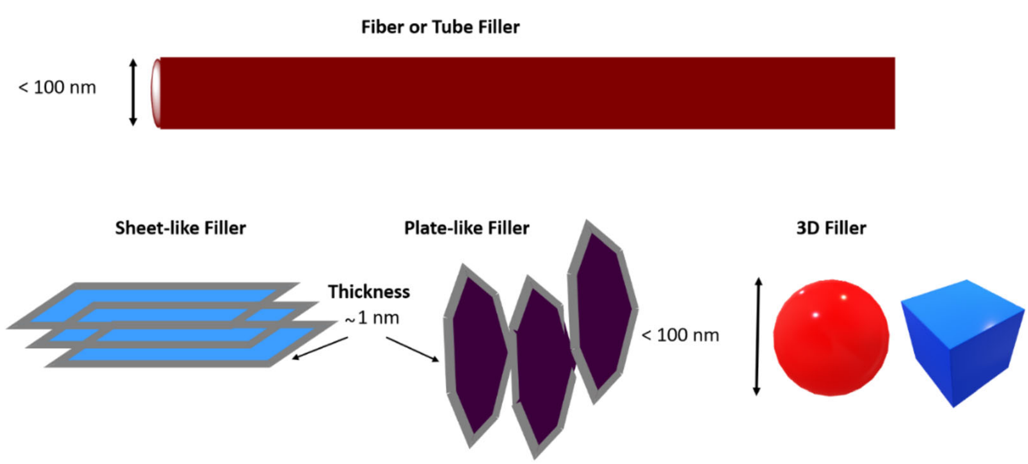

Figure 1. Schematic representation of classes of nanofillers.

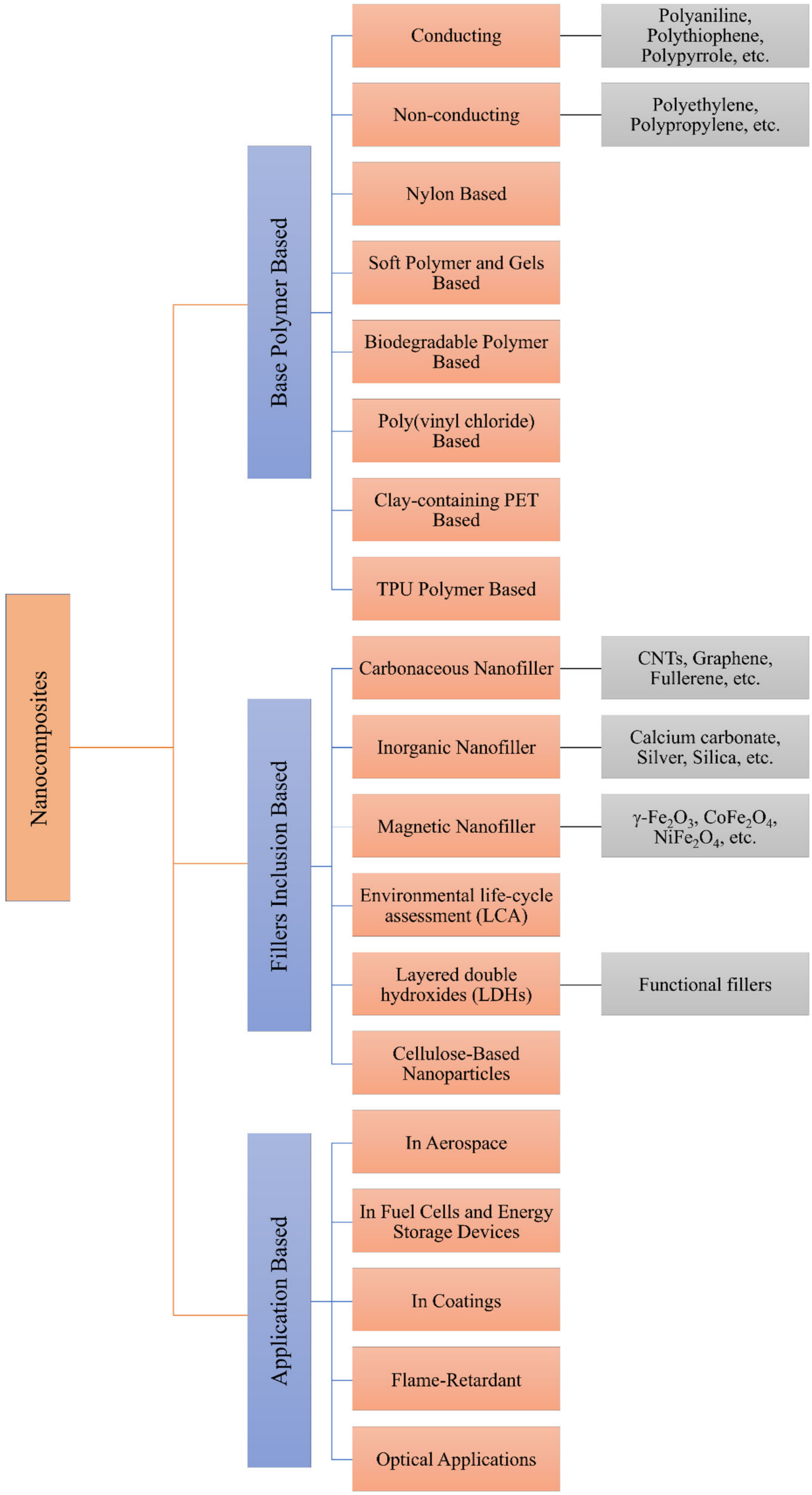

Figure 2. Classification of polymer-based nanocomposites.

and materials, research developments and advanced trends in chemicals, fibres, polymers and plastics, composites, metals, alloys, coatings, oil and gas, fuel additives, biochemical, and many other technologies will have a positive impact on several industries through their potential applications [37–41]. Notably, the arrival and application of

Figure 3. Improvements and advantages of the introduction of nanofiller into the nanocomposites.

nanotechnology in the defence sector and platforms have revolutionized numerous technological changes of an extensive range. The application of nanotechnology, which will directly and properly impart the improvement in the defence sector, comprises smart structures and materials, aerodynamics, stealth, resilience and robustness, mobility, sensing, power generation, management, etc.

Nanotechnology promises innumerable applications for defence, particularly in aerospace, sensors, nanoelectronics, energy storage, memory storage, nanorobotics, transducers, propellants and explosives, by enhancing the performances of weapon systems and devices. CNTs, an essential electro-communication component, acquire unique properties such as ballistic electron transport with enormous current-carrying capacity. This property makes them of prodigious interest in nanoelectronics. Magnetic polymer nanocomposite embodied with iron oxide nanoparticles, i.e., Fe_3O_4 and Fe_2O_3 incorporated polymer nanocomposite films used in data storage devices and media [42]. However, ceramic nanoparticles such as barium titanate and barium strontium titanate are employed for creating energy storage devices like supercapacitors [43].

4. Nanomaterials-reinforced polymer nanocomposites for defence applications

4.1 *Aerospace applications*

The aerospace field demands a combination of optimum properties with substantial weight savings, reducing fuel consumption and cost benefits. Thermosetting resins are used in aircraft manufacturing, which increases the core strength of fibre-reinforced composite parts and structural adhesives by employing core-shell technology. This fibre-reinforced composite works over temperatures –100°C to the high used temperature of the thermosetting resins. Rubber-modified epoxy resins are also used to strengthen the epoxy prepregs for aerospace requirements, improve core toughness and minimize micro-crack development in fibre-reinforced composites and structural adhesives. These epoxy resins can improve fibre wetting and adhesion to aluminium substrates [15, 44]. Bismaleimide resins are effectively made up of high-performance composites, and they are most appropriate for use in the aerospace industry. The products include bismaleimide monomers, toughening modifiers and formulated bismaleimide resins [45]. Extruded sheets of polyphenyl sulphone are designed to offer infinite interior decoration likelihoods for aircraft cabin components. These materials have excellent resistance to chemical and external impact. Polyphenyl sulphone can be produced by conventional forming apparatus for various uses, such as sidewall dividers for galleys, lavatories seating and window shades. Polymethyl methacrylate acrylic sheet has highly durable, high impact-resistance and lightweight properties that can be utilized for glazing in commercial and military aviation manufacturing [15].

Njuguna and Pielichowski [46] reviewed aerospace applications in view of nanotubes-containing polymers and their production methods. Schmidtke and Brandt [47] from European Aerospace and Defence Systems overviewed aerospace applications, covering interior airplane materials with improved fire retarding properties, such as enhanced elastic modulus and crash properties to transparent polymers with higher mechanical resilience and enhanced scratch resistance without loss of transparency. Their defence application includes impact and/or damage-resistant carbon fibre-reinforced polymers, corrosion protection, transparent materials (canopies), surface coatings for signature management, etc.

The inclusion of carbon fibres in a polymer composite is usually embedded in a resin matrix or another polymer. These composites are profoundly used in aircraft and aerospace vehicles and must be structurally extremely strong yet characteristically light in weight. However, they are prone to lightning damage since composites are poor conductors of electricity. Furthermore, a revelation to ultraviolet rays or delamination triggered by out-of-plane impact, load or moisture can significantly reduce the life of composites. Therefore, an advanced polymer nanocomposite is required with improved resistance to fracture and fatigue through an appropriate composite preparation, wherein nanoparticles/nanofillers are dispersed in a polymer matrix [48]. PNCs with carbonaceous nanofillers are promising aerospace materials to enhance lightning prevention, radiation shielding, anticorrosion and thermal properties [49, 50]. Nanotechnology appears to develop near-to-flawless materials that can increase performance safety and concurrently reduce the cost of production and maintenance of aircraft. The inclusion of silica nanoparticles with the tuned surface in an epoxy resin can be employed in many structural adhesives and fibre-reinforced composites for aerospace applications. Molecular-tuned nanofiller-incorporated resin significantly improves the compressive strength and fatigue behaviour of the fibre-reinforced composite materials prepared with this resin [51].

There has been an enormous use of nanomaterials as nanofillers to augment the properties of structural and non-structural polymers. For this purpose, the frequently employed materials in service are carbon nanotubes, nanoclays, nanofibres and graphene. CNTs have displayed significant advantages in various studies as nanofillers for different polymers because of their callous and stiff nature and exceptional electrical properties. They offer enhanced vibration and fire resistance and superior strength-to-weight ratios, making them perfect for aviation applications [52].

The properties of polymer nanocomposites make them an ideal material for their use in the aviation industry; these are rapidly being explored as alternatives for certain metals in aircraft airframes. In the recent past, nanotechnology developments by employing molecular engineering and design principles aid in the alignment and orientation of nanofillers into the polymeric matrix of super-strong fibres for ballistic armor applications [53]. Developments in weaponry that come with comparable advances in armor and nanomaterials could be modified and designed to build powerful armors. The aluminium alloy incorporated with CNTs is explored to make vehicle armor, and Krylon terminator ballistic body armors made from these materials can withstand multiple impacts. Nanostructured materials can create durable, lightweight, robust, adaptive armor and nanofibre-based outfits that better protect against projectiles.

Similarly, the so-called ‘smart materials’ should be proficient in adapting and adjusting temperature, pressure, light, stresses or hostile pH changes [54]. This is still in its primary growth stages to design and develop a suitable battle suit that will persist comfortably when worn along with lightweight and simultaneously stop bullets, monitor vital signs, defend the wearer against toxins materials, and administer first aid when needed. Only a few reports on polymer nanocomposite ballistic testing may be due to confidentiality and the absence of appropriate nanocomposite materials to produce such ballistic products. Woven fabrics are protected from light, body armor and vehicle liners, viz. kevlar. Recent development in electrospinning, particularly electrospun nanofibres spun CNTs, might assist in such applications. However, some reports are accessible for the promising application of nanocomposites in body armor [55]. The goal of defence research has now advanced searching for improved medicinal and casualty precaution units for soldiers and prolonged to using nanotechnology for better protection and enhanced connectivity through the production of lightweight, solid and multifunctional materials for clothing and armouring purposes [56]. Therefore, better-quality body armor is a significant focus for military nanotechnology research, and several different technologies are being explored.

The conducting nanofiller impregnated textiles termed smart textile show enhanced functionality of the final product. They can monitor personnel's position and physiological conditions and protection of soldiers in battle zones amidst additional technical applications. Nanotechnology-endorsed smart fabrics have become the structural blocks of cutting-edge smart textiles for many military applications, comprising military clothing, textiles and tents for military shelters.

4.2 *Detection of explosives on airport luggage*

There has been an increment in the necessity for public security to detect trace amounts of explosives due to terrorist and unlawful activities. Ensure personnel security and protection of public property is necessary. Dutta *et al* [57] described the synthesis of carbon and silver nanoparticles impregnated in graft polymers of poly(vinyl alcohol) and polythiophene in one-step free radical polymerization for the sensing of nitroaromatic compounds by fluorescence measurement. The conducting nanoparticles were used to enhance the delocalized π-electron density of the luminescent polymer. The electron-rich nanocomposites are useful for the selective detection of electron-deficient nitroaromatic explosives by the fluorescence quenching method [57].

4.3 *Fibre/textile applications*

The CNT, a discovery by Iijima in 1991 [58], prompt great interest in the application of CNTs due to their unique properties [59]. CNTs dimensions are much smaller than traditional carbon fibres with improved mechanical, electrical, optical, thermal and semiconductor properties, resulting in advancement in the functional properties of polymer nanocomposites. Further developments lead to spinning CNTs into fibres in a polymer matrix [60] and using them to produce textiles for mechanical (strength and stiffness) and electronic (electrical conductivity) applications [61, 62]. Non-woven fabrics can be directly exposed to a high-intensity light source to achieve electrical conductivity, followed by flash welding of these fibres at cross-over junctions [63]. Masking of these fibres can lead to any desired shape. Defence applications of these nanocomposites include electromagnetic and radiofrequency shielding, electrically conductive textiles, mechanical reinforcement, materials for micro-UAVs, electrical energy storage (capacitors), microwave absorption, sensors, actuators and electrostatic painting of automotive parts, etc. [64, 65].

4.4 *Carbon nanotube nanocomposites*

CNTs as the fillers in polymer matrices have vast potential for creating multifunctional materials. The combined properties of the CNTs, such as excellent electrical conductivity, high thermal conductivity, extreme mechanical strength, and polymers such as easy formability, flexibility and low density, can be gained in the developed polymer nanocomposites, which will help to build defence-related products. Glatkowski *et al* [65] reported that only a limited weight percent of oriented CNTs can be added to a wide range of thermosetting and thermoplastic polymer matrices to achieve desired properties. For defence applications, these materials include microwave absorption applications, multifunctional materials for electrical energy storage (condensers), high-strength nanotube-reinforced polymer fibres for energy absorption (ballistic protection), integrated into load-carrying structures for UAVs, electromagnetic shielding (microwave signature control), etc.

4.5 *Refractive-index tuning*

Optical fibres based on the low-cost polymer are widely used in telecommunications and optical computing applications (connectors and switches). The mismatches of the refractive index in optical fibre and other connected devices (such as semiconductors or silica optical fibre) may lead to losses. It is necessary to adjust their respective refractive indices (i.e., either raise or lower). Polymer nanocomposites can be developed to have nanofillers with different refractive indexes. Böhm *et al* [66] introduced zirconia, alumina and silica nanoparticles into the polymethyl methacrylate matrix to adjust the refractive index for polymer nanocomposite as a waveguide.

Similarly, the refractive index of surface coatings can be tuned for signature management application. Introducing these ceramic nanoparticles also helps improve the nanocomposites damage resistance (abrasion and scratching). Defence applications of such nanocomposites include optical fibres, optical connectors, switches, signature management, etc.

4.6 *Solid lubricants*

Despite various advantages such as low density and easy formability, polymers lack their applicability in continuous contact with a moving object due to the poor wear resistance. Porous bearings are impregnated with oil/grease-based lubricant to reduce friction and wear, e.g., electrical contacts, bushes forbearing, nozzles, etc. Inorganic fullerene-like (IF) nanoparticles (e.g., tungsten sulphide, WS_2) possess a hollow onion structure. These IF nanoparticles can be incorporated with polymer to improve their wear resistance and fracture toughness. Rapoport *et al* [67] added small quantities of ~ 100 nm diameter WS_2 nanoparticles to epoxy and polyacetal polymers and calculated the dry friction coefficient of the polymer and a steel disc using the pin-on-disc method. They observed that both nanocomposites reduced the dry friction coefficient to more than half. In the defence sector, these solid lubricants can be used in bearings that slide or rotate where surfaces continuously must slide over each other.

4.7 *Chemical sensors and pressure sensors*

Polymer nanocomposites can be used for sensing various chemical materials. It was reported that adding CNTs into the conducting polymer matrix increased the sensitivity and remarkably reduced power consumption. An and co-workers [68] reported the *in-situ* polymerization of pyrrole with dispersed single-wall nanotubes to form a nanocomposite porous material in conducting polypyrrole matrix. The porous structure of these nanocomposites allowed easy diffusion of the gas and detected the common atmospheric pollutant nitrogen dioxide; the nanotubes' high surface-to-volume ratio gave a sensitive sensor. Incorporating the nanotubes improves the sensitivity approximately ten times the composite compared to the polymer. An *et al* [68] observed that the nanocomposite synthesis was complex, suggesting that more improvement in sensitivity can be achieved by modifying the synthesis process. Sensors based on this material can be tuned to detect specific chemical coatings (generally in the gas phase) on the nanofibres.

Another class of chemical sensors comprises various polymers with nanofibres material and are prone to exposure to different unknown substances simultaneously. Most of them are solvents that can easily be absorbed by polymers, which leads to imbibition and changes in the electrical resistance, which are quickly and directly measurable. The sensor can detect various chemicals using a matrix of different polymers. Similar material can be applied as simple pressure sensors, e.g., as 'artificial skin' as an intermediary between man and machine (active gloves). In defence, these sensors include the identification of atmospheric pollutants, solvent vapours, flammable gases, touch sensors for interaction between operators and machines, etc.

4.8 *Porous nanocomposites*

Porous or foamed polymers are overgrowing in wide applications in textiles, sensors, smart membranes, reflective displays, fuel cells, high and low densities foams for seats/furniture and filter materials.

Porous nanocomposites can be synthesized in several ways, most common and simplest way is to include polymeric foam in a homogeneous matrix of a nanoporous material. In contrast, too complex materials may have distributed nanoparticles or nanotubes in a matrix with pores of conventional size or nanometre dimensions. Siripurapu *et al* [69] reported that incorporating nanoparticles improves the foaming properties by adding nanoparticles silica as nucleation sites for nanopore formation and using carbon dioxide as a blowing agent.

The major drawback of porous polymer foams (e.g., polyurethane) is the large surface/volume ratio that increases the release of gas and heat in case of fire. That is crucial for polymer foams, mainly in furniture, automobiles, and applicable to where a soft and deformable shock-absorbing material is needed—the introduction of nanoparticles in a flake-like morphology results in a significant reduction of the burning rate. Only few reports in this area are publicly available [70], likely due to intellectual property rights matters, but some success in this directive has been accomplished. Their applicability in the defence sector includes automotive vehicle seats, shock-absorbing materials, acoustic absorbents, etc.

4.9 *Microwave absorbers*

Nanocomposites are receiving significant attention for their capability as microwave absorbers as electrical lossy and magnetic lossy materials. Although openly published material on the same is scarce, few publicly available reports give some direction regarding the kinds of nanocomposites being investigated. Nguyen and Diaz reported [71] that the technique synthesizes polypyrrole nanocomposites with iron oxides (gamma and alpha), tungsten oxide, titanium dioxide and tin oxide. Pyrrole-containing dispersed nanoparticle metal oxides were polymerized *in situ*, then evaluated their magnetic properties without mentioning microwave properties. Glatkowski *et al* [65] describe using unsystematically and non-randomly oriented carbon nanotubes in a polymer matrix for electromagnetic shielding. A few pieces of the research reported that high-strength CNTs could be employed to develop economical microwave absorbers ranging from 8 to 24 GHz [72, 73]. They can be utilized in defence as microwave absorbers in aerospace, electrical energy storage incorporated into UAV load-carrying structures, electromagnetic shielding, polymer fibres for energy absorption, etc. Agarwal and co-workers [74] recently published reports for the potential microwave absorbing nanocomposites based on ternary core-shell nanofiller ($CoFe_2O_4$/rGO/SiO_2) with epoxy matrix, polyaniline-functionalized reduced graphene oxide/γ-Fe_2O_3/epoxy [75], aluminosilicate fibres/milled carbon fibre (MCF)/silicone resin [76], EPDM ferrite composites [77].

4.10 *Electrostatic charge dissipation space*

Many applications of CNTs into polymer nanocomposites in thin films are related to electrical conductivity. A severe problem on spacecraft is the dissipation of static charge. It requires an unreactive material to the space environment. They must face atomic oxygen, rapid and extreme temperature changes, intense ultraviolet radiation and charged particle irradiation; these factors are sufficiently electrically conductive. Smith *et al* [78] from NASA observed that sufficient conductivity related to eliminating static discharge could be attained by applying polyimide nanocomposite containing about 0.03 wt% nanotubes.

Zeng and Liu [79] investigated the resistance against radiation on a styrene-butadiene-styrene/clay nanoparticles nanocomposite and observed adequate resistance when uncovered to γ-radiation. This stability of the resultant nanocomposite was attributed to two effects of the nanoparticle's additions. First, the flake-like clay particles act passively to protect the polymer from radiation. Second, the nanoparticles act actively as sinks for damaged polymer chains grafted onto the nanoparticle's surfaces.

Charati *et al* [80] and Mylvaganam and Zhang [81] reported a method for the production of conductive composites via sonication of an organic polymer (poly(arylene ether) with single-walled carbon nanotube (SWNTs) in an ultrasonicator to disperse the SWNTs, then polymerization the organic polymer precursor using shear and elongational forces. They observed that in doing so, at least a portion of the CNTs could be functionalized either at the sidewall or hemispherical ends. Defence applications of polymer nanocomposites include lightning protection for aerospace structures and systems, anti-static coatings for components and apparatus, specifically in space systems, etc.

4.11 *Ultraviolet irradiation resistance*

Commonly used polymers tend to degrade when kept under ultraviolet irradiation for a few weeks or months. Degradation decreases their mechanical properties (like strength and fracture toughness), making the polymer frangible. Traditional carbon fibre/epoxy composites currently employed in space applications are exposed to the atmosphere and suffer. Jiang *et al* [82] reported that adding titanium dioxide nanoparticles to the epoxy matrix in a carbon fibre composite improved the resistance against degradation by ultraviolet irradiation by approximately 50%. At the same time, the interlaminar shear strength improved by 80%. These materials can be utilized to improve the material properties such as reduction in outgassing, improved effective load and extension in a lifetime. Defence applications of polymer nanocomposites include components, textiles and coatings exposed to paint, sunlight and surface protection.

4.12 *Industrial applications*

The increased electrical conductivity of nanocomposites has led to their use in various industrial applications. Plastic components like bumpers, wing mirrors, door handles, etc., are typically manufactured by injection mould and must be painted. Generally, electrostatic spray painting can be used in this scenario but is limited to the conductive material. Earlier, the painting was done by immersing them in conductive paint; this method had drawbacks like the inability to provide the required mechanical strength or thickness. Recently, a coating made from nanotubes dispersed in a polymer has been designed and used in production. The automotive industry is very frugal as-is; thus, this new technological solution becomes more appealing and can provide real cost/performance benefits [83].

Moreover, a more delicate coating is needed to achieve good electrical conductivity outcomes and improve smoothness and surface quality. The advantages of polymer nanocomposites include weight savings when used in an automotive vehicle, fuel-saving and reduced transportation costs. Other benefits include improved appearance, sharper quality lines, grain patterns, enhanced paint ability, better scratch/mar performance, an extensive processing window, reduced paint delamination, consistent physical and mechanical properties, retaining the ductility at low temperature, and lower flammability, improved recyclability, etc. In this field, defence applications of polymer nanocomposites include operating and lightly loaded components, currently assembled up of plastics or light alloy where injection moulded plastic can replace metal components such as handles, fasteners and parts of portable weapons systems, etc.

4.13 *Reduction in signature*

Openly published and publicly available literature in this field is rare as it is confidential. Much research and development in this field for the advancement and use of polymer nanocomposites are being developed. These include composites for tailored electromagnetic radiation shielding, conformal coating, electrostatic dissipative polymers (ceilings), electrostatic discharge film, non-metallic compliant conductive materials for airframe electrical conductivity, etc.

Camouflage materials can be dynamically tuned and allow defence operations to make personnel and equipment either highly visible or concealed, depending on the demands of the situation. The use of electrochromic materials can achieve this. De Longchamp and Hammond [84] reported a high-contrast electrochromic nanocomposite of poly(ethyleneimine) and Prussian Blue nanoparticles. In defence, such materials are required for all systems and platforms where signature management is needed.

4.14 *Protection against ballistics*

Only a few reports are available for ballistic testing polymer nanocomposites. These materials are a matter of secrecy, often due to the scanty suitable forms of nanocomposite materials. Kevlar and other woven materials, such as body armors and vehicle linings, are commonly used for light protection. Electrospun nanofibres are likely to be applicable in this context, but realistic resting is currently impossible due to the limited quantity of available materials. However, there are reports of the recent use of spun carbon nanotubes [85]. They are thought to possess powerful mechanical properties mixed with powerful elastic properties, which would make them valuable for defence applications.

Ostermayer *et al* [86] reported calculating the V50 behaviour of initial nylon 6-clay nanocomposites by applying fragment simulating projectile method. The superficial results revealed that the nanocomposite's ballistic limit stood lower compared to unreinforced polymer and, hence, unsuitable for use as an armor material.

There are reports that promising nanocomposite applications may be termed in-body armor [87–89]. Shear thickening fluids comprise liquids with dispersed particles and being sheared rapidly by exterior stress stiffens and resists deformation. U.S. Army Research Laboratory [90] reported promising results of combined inorganic nanoparticles (i.e., silica) incorporated in polyethylene glycol. When impregnated into Kevlar®, the energy absorbability of the same is greatly enhanced in the resultant shear thickening fluid. In this case, the ballistic performance (absorbed energy) becomes higher than two times. The performance of 4-layers of Kevlar® impregnated with the shear thickening fluid in energy absorption is more elevated than ten layers without the shear thickening fluid. In practice, this result is much more flexible for armor with high ballistic protection, reducing the total weight.

In defence, polymer nanocomposites are employed frequently for potential applications, including body armor and personal armor. Flexibility and mobility are essential and need protection against blunt weapons (stones, bars and sticks). The current technology employed is not possible for arms and legs because of the flexibility required in the armor to do the same.

4.15 *Fire retardation*

Fire resistance is regarded as one of the most significant properties of nanocomposites. Polymers are generally prone to fire and lack the resistance exposed to fire. They get burnt quickly and release additional heat, poisonous gases and soot in large quantities. In addition, the polymer melts due to its low melting point and drips. Polymer spreads igniting droplets during the fire, which are a fire hazard and further spread the fire. When applied in the defence sector, fire can lead to a disaster, mainly when it circulates on board a ship, ground vehicle, aircraft, ships and submarines. Chemical additives (such as halogenated hydrocarbon) are widely used to reduce the flammability of polymers; however, they have numerous terrible side effects. When set on fire, halogens like bromine or chlorine release highly toxic and combustible gases. Moreover, it has been observed that these compounds, when accidentally consumed or inhaled by living hoods and ultimately by humans upon disposal, cause health problems [91]. Halogenated fire retardants will be deemed unfit for use by environmental legislation in a few years.

Polymers containing a small weight percent of nanoparticle clays have significantly increased the fire resistance in various ways, as also described by Gilman *et al* [92]. The thermal resistance and properties of the polymer nanocomposite can be enhanced, leading to delayed melting and dripping, and the burning rate is significantly lowered by more than half. When the clay nanoparticles are present, they reduce the diffusion of volatiles (the fuel) from polymer decomposition to the burning surface and, at the same time, reduce the diffusion of air to prevent oxidation into the polymer. In addition, they form a protective upper crust, which protects the unburnt polymer and exposure to radiative heating. Another benefit of using clay-incorporated polymers is that they significantly increase the mechanical capabilities of the polymer self, which can be used to improve the component load-carrying capacity or reduce weight and/or thickness. This effect has been observed for all available thermosetting and thermoplastic polymers. Unexpectedly, an identical positive impact is also reported on polypropylene/carbon nanotube nanocomposites. It might be thought that as they are highly conducive to heat from the carbon nanotube, they might radiate to the polymer and enhance its burning. Kashiwagi *et al* [93] reported that it is not so. Defence applications of such polymer nanocomposites include reduced risk of fire in enclosed spaces, like that of vehicles on all air, ground or water surface vessels (ships) particularly can benefit by replacing existing polymers, such as epoxy and vinyl ester in glass- and carbon-fibre-reinforced composites, by retention of the mechanical properties.

4.16 *Corrosion protection*

Generally, to protect against corrosion is prevented by painting the surface with surface coating agents that should be resistant to chemical and mechanical damage such as salts, acids, bases scratching and abrasion. Moreover, the coating should have a coefficient of thermal expansion close to that of the metal not to crack when exposed to temperature. Currently, electronic circuits have increased the need for corrosion protection. Off-the-shelf commercial products are being used (COTS) in defence applications, which has led to the necessity to protect portable and small electronic devices and their robustness and reliability. Polymer nanocomposites can add a lot of advantages, but their application in this field has not been studied extensively. Because of their higher hardness and improved elastic modules, they can provide better scratch and abrasion resistance. They are also better barriers to diffusion, which can be very useful in materials used for packaging. Gentle and Baney [94] reported the findings of preliminary experiments on the use of silicone nanocomposite coating reinforced with silica to protect electronic circuits and aluminium surfaces. During salt fog testing, it was observed that the survival rates enhanced by up to 100 times [94].

Defence applications of polymer nanocomposites can be applied to protect from corrosion in aerospace (at average or low temperatures, not appropriate for temperatures above $\sim 150°C$), protection of electronic circuits from corrosion, etc.

4.17 *Actuators*

Autonomous systems have led to a rapid increase in actuators and have been speculated to continue in future. The actuators traditionally used in the electric motor are not in high demand anymore as the need for actuators is now relatively small. Moreover, they require a high-power level, and a gearbox is often needed to facilitate the change of rotary motion to linear motion. Nanocomposite-based actuators are advantageous over others as they often require lower power levels and can produce linear motion directly. Koerner *et al* [95] reported that dispersion of carbon nanotube (< 5 vol%) in a polyurethane thermoplastic polymer resulted in nanocomposite that could store (and discharge when required) 50% more strain energy in comparison to an unreinforced polymer. In contrast to conventional additives (e.g., carbon black), the lower addition of carbon nanotubes allowed indirect (infrared) or directed (Joule heating) activation resulting in nanocomposite having improved properties.

Application of shape memory polymers is reported and used in some cases. However, shape memory polymers are not strong enough as they have low recovery stress and are non-useful for broader applications. Inert silicon carbide nanoparticles provide a mechanical restraint to commercial shape memory polymer. Gall *et al* [96] increased the recovery stress by up to 50% without degrading other properties.

Courty *et al* [97] demonstrated an unexplored actuator response driven by an electric field with multiwalled carbon nanotubes in a nematic elastomer of polysiloxane. They synthesized a nanocomposite with embedded and aligned CNTs with fruitful dielectric anisotropy, which was exponentially higher than usual liquid crystals. Ounaies *et al* [98] reported a method for creating actuating composite materials with polarizable moieties (e.g., polyimide) and CNTs. Defence applications of such actuators are in UAVs, especially in micro-UAVs.

4.18 *Diffusion barriers*

A new property discovered in nanocomposites that is unique to them is their ability to protect against gases and volatile solvents. Nanoparticles contribute to this property as they are immune to diffusing molecules. Polymer chains directly connected to nanoparticles are also suggested that are more rigidly bound than chains at a distance from the nanoparticles, leading to the particle's adequate size being larger than the nanoparticles. To significantly improve barrier properties, small weight percent of nanoparticles is required. The suitability of materials for various applications increased because of the improved barrier properties. Wilson, the tennis equipment manufacturer, has shown the use of a rubber-based nanocomposite to create a gas-tight lining for tennis balls [25]. The commercial application shows that the pressure inside the newer tennis balls is maintained for nearly double the duration.

Prevention of air diffusion and odours is essential in the food packaging industry as they require air-tight packaging. Several 'tetra pack' and liquid containers are made-up of several layers, with a layer of aluminium as a waterproof barrier to prevent the air from spoiling the contents. The water vapour lost from the food material can lead to 'drying-out'; alternatively, the entry of water vapour into the food can lose crispness. The U.S. Army field-tested individual ready-to-eat food packaged containers made of nanocomposite and claimed to remain 'fresh' for 3 years.

Nanocomposite enhances the barrier properties to prevent a gas's or liquid's diffusion, including enhanced fire resistance and corrosion.

Nanocomposites can be used in gas-tight, food and fuel containers in the defence sector and can replace currently used elastomers like rubber.

4.19 *Sensors*

Kong *et al* [99] reported chemical sensors based on individual SWNTs. The electrical resistance of semiconducting SWNTs changed drastically on exposure to gases like NO_2 or NH_3. While the common electrical sensor materials, such as carbon black polymer composites, operate at high temperatures for notable sensitivity. In contrast, the sensors made up of SWNTs showed a fast response and better sensitivity at ambient temperature.

Ajayan *et al* [100] reported a controlled method to produce free-standing nanotube–polymer composite films that can be utilized for nanosensors, containing a minimum of a single conductive channel consisting of an array of embedded aligned CNTs in a matrix (e.g., poly(dimethylsiloxane)). The resultant material is applicable to speculate the real-time physical condition of the material used for chassis and airplane wings while the plane is in flight. These materials can detect and identify poisonous gases, solvent vapours, chemical warfare agents, etc., and touch sensors between operators and machines (table 1).

Table 1. Polymer-based nanocomposites properties and defence applications.

Polymer nanocomposite	Matrix	Nano filler/fibre	Property	Applications	Refs.
CB/Epoxy	Epoxy	CB	Reducing static electricity	Aerospace application	[48]
Carbon/Ag/PVA/PT	PVA/PT	Carbon, Ag	Electrical	Sensor	[57]
CNT/Ppy	Ppy	CNT	Electrical	Sensor	[68]
$CoFe_2O_4$/rGO/SiO_2 EPOXY nanocomposite	Epoxy resin + harderner	$CoFe_2O_4$/rGO/SiO_2 ternary nanofiller	Magnetic and electrical	Microwave absorption application	[75]
rGO/PANI/γ-Fe_2O_3 epoxy nanocomposite	Epoxy resin + harderner	rGO/PANI/γ-Fe_2O_3 ternary nanofiller	Magnetic and electrical	EMI shielding	[76]
Prussian blue/ polyethyleneimine	Polyethyleneimine	Prussian blue nanoparticles	Electrical	Defence application	[84]
CNT/PU	PU	CNT	Electrical	Actuator	[95]
CNT/ poly(dimethylsiloxane)	Poly(dimethylsiloxane)	CNT	Electrical	Nanosensor	[100]
$NiFe_2O_4$/polyurethane nanocomposite	Polyurethane	$NiFe_2O_4$	Magnetic	Microwave absorption application	[101]
MWCNT/Twaron/epoxy	Epoxy	MWCNT, Twaron	Improved fracture toughness, energy absorption and ballistic resistance	Ballistic application	[102]
MWCNT/Kevlar/epoxy	Epoxy	MWCNT, Kevlar	Izod impact strength, energy absorption and ballistic resistance	Ballistic application	[103]
MWCNT/E-glass/epoxy	Epoxy	MWCNT, E-glass	Good impact strength, energy absorption and ballistic resistance	Ballistic application	[104]
GO/epoxy/natural fibre	Epoxy	GO, natural fibre	High elastic modulus, large specific surface area, good thermal and electrical conductivity	Ballistic impact application	[105, 106]
Graphene/epoxy or polypropylene/glass fibre	Epoxy or polypropylene	Graphene nanoparticles, glass fibre	High young's modulus, fracture toughness and tensile strength	Ballistic impact application	[107, 108]
Nanoclay/glass fibre/ epoxy	Epoxy	Nanoclay, glass fibre	Good stiffness, hardness, strength and energy absorption	Ballistic impact application	[109]
IF-WS_2/Aramid/PVB	PVB	IF-WS_2, Aramid	Enhanced Mechanical, impact resistance and glass transition temperature	Ballistic protection	[110]
B_4C/UHMWPE	UHMWPE	B_4C	Improved storage modulus and low bullet penetration	Ballistic protection	[111]
Kenaf fibre/PAC/ polyester	Polyester	PAC, Kenaf fibre	EMI shielding material	EMI shielding, military, aerospace	[112]
Graphite/aluminium	Aluminium	Graphite	Hubble Space Telescope's antenna boom	Aerospace	[113]
CNT/PI	PI	CNT	Improved strength and modulus	Aerospace	[114]
SWCNT/PVA	PVA	SWCNT	Good stability, strength, stiffness, and toughness	Military automotive and defence	[115]
CNT/epoxy	Epoxy	CNT	Improved peeling and tensile strength	Military automotive and defence	[116]

Table 1. continued

Polymer nanocomposite	Matrix	Nano filler/fibre	Property	Applications	Refs.
CB/PP	PP	CB	Absorption loss to total attenuation	EMI	[117]
Fe-MWCNT/epoxy	Epoxy	Fe-MWCNT	Microwave absorption	EMI	[118]
Graphene/PS	PS	Graphene	Microwave absorption	EMI	[119]
Fe_3O_4/rGO/PS	PS	Fe_3O_4/rGO	Microwave absorption	EMI	[120]
SWCNTs/GNS/PANI	PANI	SWCNT	Microwave absorption	EMI	[121]
Graphene/Fe_3O_4/PANI	PANI	Graphene/Fe_3O_4	Microwave absorption	EMI	[122]

5. Future perspective

It is well known that the defence aerospace industry was the first to introduce composites. The same sector will continue to demand more efficient, lighter, and stronger crafts in the future. This may lead to aircraft being constructed entirely with composite materials instead of metal. It will be the individual parts primarily built with metals and composites. Moreover, better and more effective vibrational dampening and more lightweight properties will push materials manufacturers to research and upgrade the current composite systems. Thus, aerospace manufacturers require working with material scientists and manufacturers to create, innovate, facilitate, and enhance better quality, safer, quieter and more efficient aircraft for military and civilian purposes.

Nanotechnology develops defence active sensing sensors to detect corrosion damage, substrate integrity, etc., and protect from the surroundings, i.e., radiation, gases, chemicals, temperature, strain, etc. Nanotechnology has already impacted battlespace systems with information and signal processing, autonomy and intelligence concerns.

6. Summary and conclusions

Nanocomposite technology has many actual and potential applications in the rapidly growing defence field. They are helpful in all circumstances needed for multiple properties, where the total performance outweighs one specific property. They can significantly impact the defence systems, two in particular. These nanocomposites are profoundly assimilated into multifunctional materials for crewless aerospace vehicles (UAVs).

UAVs are used to progress and augment highly recommended aspects of survivability and the functionality of soldiers individually. It is safe to say that PNCs in the mid and extended term will be a common aspect of life, as plastics were in the recent past century. A wide variety of solar cells, automotive, aerospace, packaging, electronic goods, domestic goods, etc., will benefit substantially from a new series of advanced materials.

Over more than two decades, the research and developments have resulted in unprecedented nanocomposite technology that has profited the defence and society. Hopefully, soon, we can expect the outcome of nanomaterial and their systems for military purposes by making use of the unique properties of PNCs, such as self-repair, corrosion resistance, sensing, selective removal, ability to change physical properties of coatings, colourizing and vigilant to logistics staff for tanks or weaponry when requiring ampler repair.

To conclude, nanotechnology might promise a future of developing multifunctional materials for multipurpose contributions such as building and maintaining lighter aircraft, ships, and spacecraft, which are smarter, safer, faster air, more innovative, and more efficient land and sea vehicles with improved structural integrity. Nanocomposites are advantageous in defence-related applications. Further research in this direction with collaboration from various industries and research institutions may increase their use in various defence-related applications.

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References

[1] El-Fatatry A 2007 *Defence applications* in *Loughborough Univ (United Kingdom)*
[2] Altmann J 2004 *Secur. Dialogue* **35** 61
[3] Kladitis P E 2010 *How small is too small true microrobots and nanorobots for military applications in 2035* in *Air Command and Staff College, Air University Maxwell Air Force Base United State*
[4] Tan Y J, Wu J, Li H and Tee B C K 2018 *ACS Appl. Mater. Interfaces* **10** 15331
[5] Pinnavaia T J and Beall G W (eds) 2000 *Polymer-clay nanocomposites* (New York: Wiley) https://doi.org/10.1002/pi.882
[6] Harris P J 2004 *Int. Mater. Rev.* **49** 31
[7] Gay D E 1996 *Encapsulated ferromagnetic particles suitable for high temperature use* US Patents, 5,563,001
[8] Heilmann A 2003 *Polymer films with embedded metal nanoparticles Springer Science & Business Media* p 52
[9] Muisener P, Clayton L, D'Angelo J, Harmon J, Sikder A, Kumar A *et al* 2002 *J. Mater. Res.* **17** 2507
[10] Sun S, Anders S, Hamann H F, Thiele J-U, Baglin J E E, Thomson T *et al* 2002 *J. Am. Chem. Soc.* **124** 2884
[11] Oréfice R, Discacciati J, Neves A, Mansur H and Jansen W 2003 *Polym. Test.* **22** 77
[12] Lagashetty A, Basavaraj S, Bedre M and Venkatarman A 2009 *J. Metall. Mater. Sci.* **51** 297
[13] Vasil'kov A Y, Zachernyuk B, Karpikov Z, Volkov I, Zubavichus Y V, Veligzhanin A *et al* 2007 *Russ. J. Appl. Chem.* **80** 2136
[14] Singh K, Ohlan A, Kotnala R, Bakhshi A and Dhawan S 2008 *Mater. Chem. Phys.* **112** 651
[15] Ramdani N (ed) 2019 *Polymer nanocomposites for advanced engineering and military applications* (IGI Global, Pennsylvania)
[16] Verma M, Verma P, Dhawan S K and Choudhary V 2015 *RSC Adv.* **5** 97349
[17] Fu Y, Michopoulos J and Song J-H 2015 *J. Polym. Sci. B Polym. Phys.* **53** 1292
[18] Vas J V and Thomas M J 2018 *IEEE Trans. Electromagn. Compat.* **60** 376
[19] Wang L, He X and Wilkie C A 2010 *Materials* **3** 4580
[20] Rahman M M, Islam M, Roy R, Younis H, AlNahyan M and Younes H 2022 *Lubricants* **10** 281
[21] Kanu N J, Gupta E, Vates U K and Singh G K 2021 *Chapter Three -An insight into smart self-lubricating composites* in *Smart polymer nanocomposites* S A Bhawani, A Khan and M Jawaid (eds.) (Woodhead Publishing) p 85–101 https://doi.org/10.1016/B978-0-12-819961-9.00012-8
[22] Peng T, Xiao R, Rong Z, Liu H, Hu Q, Wang S *et al* 2020 *Chem. Asian J.* **15** 3915
[23] Earle M D and Earle R L 2000 *Building the future on new products* (Leatherhead: Leatherhead Food RA) *Pub.*
[24] Gerhard D, Brem A and Voigt K-I 2008 *Int. J. Technol. Mark.* **3** 203
[25] Sen M 2020 *Nanotechnology and the environment* (London: IntechOpen) p 1–12
[26] Pielichowski K and Pielichowska K 2019 *Thermochim. Acta* **675** 140
[27] Akpan EI, Shen X, Wetzel B and Friedrich K 2019 in *Polymer composites with functionalized nanoparticles* K Pielichowski and T M Majka (eds.) (Elsevier) p 47
[28] Harito C, Bavykin D V, Yuliarto B, Dipojono H K and Walsh F C 2019 *Nanoscale* **11** 4653
[29] Harussani M M, Sapuan S M, Nadeem G, Rafin T and Kirubaanand W 2022 *Def. Technol.* **18** 1281
[30] Ebrahimi F, Hafezi P and Dabbagh A 2021 *Def. Technol.* **17** 226
[31] Arefi M, Tabatabaeian A and Mohammadi M 2021 *Def. Technol.* **17** 64
[32] Kumar J and Verma R K 2022 *Def. Technol.* **17** 1671
[33] Singh K and Tripathi R P 2020 *Curr. Med. Chem.* **27** 3386
[34] Singh K and Kulkarni S S 2022 *J. Med. Chem.* **65** 8525
[35] Marchesan S and Prato M 2013 *ACS Med. Chem. Lett.* **4** 147
[36] Jiang X, Lin M, Huang J, Mo M, Liu H, Jiang Y *et al* 2020 *Front. Chem.* **8** 758
[37] Dixit A, Kumar N, Bag D S, Agarwal K, Sharma D K and Eswara Prasad N 2019 *Adv. Mater. Lett.* **10** 431
[38] Agarwal K, Prasad M, Katiyar M, Kumar R and Prasad N E 2019 *Silicon* **11** 1035
[39] Agarwal K, Prasad M, Sharma R and Setua D K 2014 *Int. J. Energy Environ. Eng.* **4** 47
[40] Agarwal K, Prasad M, Sharma R and Setua D 2011 *Polym. Test.* **30** 155
[41] Agarwal K, Setua D and Mathur G 2002 *Def. Sci. J.* **52** 337
[42] Novakova A, Lanchinskaya V Y, Volkov A, Gendler T, Kiseleva T Y, Moskvina M *et al* 2003 *J. Magn. Magn. Mater.* **258** 354
[43] Riggs B C, Adireddy S, Rehm C H, Puli V S, Elupula R and Chrisey D B 2015 *Mater. Today Proc.* **2** 3853
[44] Wang B, Bai Y, Hu X and Lu P 2016 *Compos. Sci. Technol.* **127** 149
[45] Landman D 1986 *Advances in the chemistry and applications of bismaleimides developments in reinforced plastics—5* (Berlin: Springer) p 39
[46] Njuguna J and Pielichowski K 2004 *Adv. Eng. Mater.* **6** 193
[47] K. Schmidtke and Brandt J 2004 *Polymer nanocomposites for aeronautic applications: from dream to reality? Personal communication*
[48] Yadav R, Tirumali M, Wang X, Naebe M and Kandasubramanian B 2020 *Def. Technol.* **16** 107

[49] Kausar A 2022 *J. Thermoplast. Compos. Mater.* https://doi.org/10.1177/08927057221139590
[50] Yadav G, Gupta S K, Singh K, Jaiswal R, Zacharia T J and Agarwal K 2022 *Silicon*. https://doi.org/10.1007/s12633-022-02212-6
[51] Manjunatha C M and Srihari S 2022 *Trans. INAE* **7** 501
[52] Mucha M, Krzyzak A, Kosicka E, Coy E, Kościński M, Sterzyński T *et al* 2020 *Materials* **13** 2696
[53] Tam D, Ruan S, Gao P and Yu T 2012 *High-performance ballistic protection using polymer nanocomposites Advances in military textiles and personal equipment* (Sawston: Woodhead Publishing) p 213
[54] Bogue R 2014 *Assembl. Autom.* **34** 16
[55] Mohd Nurazzi N, Asyraf M M, Khalina A, Abdullah N, Sabaruddin F A, Kamarudin S H *et al* 2021 *Polymers* **13** 1047
[56] Wu S, Sikdar P and Bhat G S 2022 *Def. Technol.* https://doi.org/10.1016/j.dt.2022.06.007
[57] Dutta P, Chakravarty S and Sarma N S 2016 *RSC Adv* **6** 3680
[58] Iijima S 1991 *Nature* **354** 56
[59] Dresselhaus M S, Dresselhaus G and Eklund P C 1996 *Science of fullerenes and carbon nanotubes: their properties and applications* (Amsterdam: Elsevier)
[60] Fong H, Liu W, Wang C-S and Vaia R A 2002 *Polymer* **43** 775
[61] Haggenmueller R, Gommans H, Rinzler A, Fischer J and Winey K 2000 *Chem. Phys. Lett.* **330** 219
[62] Haggenmueller R, Zhou W, Fischer J and Winey K 2003 *J. Nanosci. Nanotechnol.* **3** 105
[63] Huang J and Kaner R B 2004 *Nat. Mater.* **3** 783
[64] Baughman R H, Zakhidov A A and De Heer W A 2002 *Science* **297** 787
[65] Glatkowski P, Mack P, Conroy J, Piche J and Winsor P 2002 *Electromagnetic shielding composite comprising nanotubes (Google Patents)*
[66] Böhm J, Haußelt J, Henzi P, Litfin K and Hanemann T 2004 *Adv. Eng. Mater.* **6** 52
[67] Rapoport L, Nepomnyashchy O, Verdyan A, Popovitz-Biro R, Volovik Y, Ittah B *et al* 2004 *Adv. Eng. Mater.* **6** 44
[68] An K H, Jeong S Y, Hwang H R and Lee Y H 2004 *Adv. Mater.* **16** 1005
[69] Siripurapu S, DeSimone J M, Khan S A and Spontak R J 2004 *Adv. Mater.* **16** 989
[70] Pethrick R A 2010 in M Fan, C-P Huang, A E Bland, Z Wang, R Slimane and I Wright (eds) *Environanotechnology* (Amsterdam: Elsevier) p 213
[71] Nguyen M T and Diaz A F 1994 *Adv. Mater.* **6** 858
[72] Sharon M, Pradhan D, Zacharia R and Puri V 2005 *J. Nanosci. Nanotechnol.* **5** 2117
[73] Bai X, Zhong D, Zhang G, Ma X, Liu S, Wang E *et al* 2001 *Appl. Phys. Lett.* **79** 155
[74] Jaiswal R, Agarwal K, Pratap V, Soni A, Kumar S, Mukhopadhyay K *et al* 2020 *Mater. Sci. Eng. B* **262** 114711
[75] Jaiswal R, Agarwal K, Kumar R, Kumar R, Mukhopadhyay K and Prasad N E 2020 *Soft Matter* **16** 6643
[76] Katiyar M, Prasad M, Agarwal K, Singh R K, Kumar A and Prasad N E 2018 *Silicon* **10** 1831
[77] Katiyar M, Prasad M, Agarwal K, Singh R K, Kumar A and Prasad N E 2017 *J. Reinf. Plast. Compos.* **36** 754
[78] Smith J G Jr, Delozier D M, Connell J W and Watson K A 2004 *Polymer* **45** 6133
[79] Zeng J and Liu L 2004 *J. Mater. Chem.* **14** 209
[80] Charati S G, Dhara D, Elkovitch M, Ghosh S, Mutha N, Rajagopalan S *et al* 2005 *Electrically conductive compositions and method of manufacture thereof*. WO2005044862A2
[81] Mylvaganam K and Zhang L C 2007 *Recent Pat. Nanotechnol.* **1** 59
[82] Jiang L, He S and Yang D 2003 *J. Mater. Res.* **18** 654
[83] Rich A, Collins P and Hagerstrom J 2002 in *SAE 2002 World Congress & Exhibition* p 2002
[84] DeLongchamp D M and Hammond P T 2004 *Adv. Funct. Mater.* **14** 224
[85] Savage S 2004 *Defence applications of nanocomposite materials* (Swedish: Defence Research Agency Kista Sweden)
[86] Ostermayer D, Beyer F L, Dehmer P G and Klusewitz M A 2001 in *Army Research Lab Aberdeen Proving Ground Md Weapons and Materials Research*
[87] Wagner N J 2003 *Novel flexible body armor utilizing shear thickening fluid (STF) composites* in 14th International conference on composite materials (San Diego, CA)
[88] Lee Y S and Wagner N J 2003 *Rheol. Acta* **42** 199
[89] Lee Y S, Wetzel E D and Wagner N J 2003 *J. Mater. Sci.* **38** 2825
[90] Wetzel E D, Lee Y, Egres R, Kirkwood K, Kirkwood J and Wagner N 2004 *The effect of rheological parameters on the ballistic properties of shear thickening fluid (STF)-kevlar composites* in AIP conference proceedings. *American Institute of Physics* p 288
[91] Hahladakis J N, Velis C A, Weber R, Iacovidou E and Purnell P 2018 *J. Hazard. Mater.* **344** 179
[92] Gilman J W, Kashiwagi T and Lichtenhan J D 1997 *Nanocomposites: a revolutionary new flame retardant approach* in International sampe symposium and exhibition *Sampe society for the advancement of material* p 1078
[93] Kashiwagi T, Grulke E, Hilding J, Groth K, Harris R, Butler K *et al* 2004 *Polymer* **45** 4227
[94] Gentle T E and Baney R H 1992 *MRS Online Proceedings Library (OPL)* 274
[95] Koerner H, Price G, Pearce N A, Alexander M and Vaia R A 2004 *Nat. Mater.* **3** 115
[96] Gall K, Dunn M L, Liu Y, Finch D, Lake M and Munshi N A 2002 *Acta Material.* **50** 5115
[97] Courty S, Mine J, Tajbakhsh A and Terentjev E 2003 *Europhys. Lett.* **64** 654
[98] Ounaies Z, Park C, Harrison J S, Holloway N M and Draughon G K 2008 *Sensing/actuating materials made from carbon nanotube polymer composites and methods for making same* US *Patents* 7,402,264
[99] Kong J, Franklin N R, Zhou C, Chapline M G, Peng S, Cho K *et al* 2000 *Science* **287** 622
[100] Ajayan P, Lahiff E, Stryjek P, Ryu C Y and Curran S 2010 *Embedded nanotube array sensor and method of making a nanotube polymer composite* (*US Patents*) 7,673,521
[101] Agarwal K, Prasad M, Katiyar M, Jaiswal R, Kumar S and Prasad N E 2020 *J. Appl. Polym. Sci.* **137** 48645
[102] Hanif W W, Risby M and Noor M M 2015 *Procedia Eng.* **114** 118

[103] Taraghi I, Fereidoon A and Mohyeddin A 2014 *Steel Compos. Struct.* **17** 825
[104] Rahman M, Hosur M, Zainuddin S, Vaidya U, Tauhid A, Kumar A *et al* 2013 *Int. J. Impact Eng.* **57** 108
[105] Costa U O, Nascimento L F C, Garcia J M, Monteiro S N, Luz F S D, Pinheiro W A *et al* 2019 *Polymers* **11** 1356
[106] Bizao R A, Machado L D, de Sousa J M, Pugno N M and Galvao D S 2018 *Sci. Rep.* **8** 1
[107] Liang J-Z, Du Q, Tsui GC-P and Tang C-Y 2016 *Compos Part B Eng.* **95** 166
[108] Domun N, Hadavinia H, Zhang T, Liaghat G, Vahid S, Spacie C *et al* 2017 *Nanocomposites* **3** 85
[109] Rafiq A, Merah N, Boukhili R and Al-Qadhi M 2017 *Polym. Test* **57** 1
[110] Simić D M, Stojanović D B, Dimić M, Mišković K, Marjanović M, Burzić Z *et al* 2019 *Compos. Part B Eng.* **176** 107222
[111] da Silva Chagas N P, de Oliveira Aguiar V, da Costa Garcia Filho F, da Silva Figueiredo AB-H, Monteiro S N, Huaman N R C *et al* 2022 *J. Mater. Res. Technol.* **17** 1799
[112] Xia C, Zhang S, Ren H, Shi S Q, Zhang H, Cai L *et al* 2015 *Materials* **9** 10
[113] Hihara L and Latanision R 1994 *Int. Mater. Rev.* **39** 245
[114] Hu D, Xing Y, Chen M, Gu B, Sun B and Li Q 2017 *Compos. Sci. Technol.* **141** 137
[115] Lee W J, Clancy A J, Fernández-Toribio J C, Anthony D B, White E R, Solano E *et al* 2019 *Carbon* **146** 162
[116] Marriam I, Xu F, Tebyetekerwa M, Gao Y, Liu W, Liu X *et al* 2018 *Compos. Part A Appl. Sci. Manufact.* **110** 1
[117] Al-Saleh M H and Sundararaj U 2012 *J. Phys. D Appl. Phys.* **46** 035304
[118] Liu Y, Song D, Wu C and Leng J 2014 *Compos. Part B Eng.* **63** 34
[119] Yan D-X, Ren P-G, Pang H, Fu Q, Yang M-B and Li Z-M 2012 *J. Mater. Chem.* **22** 18772
[120] Chen Y, Wang Y, Zhang H-B, Li X, Gui C-X and Yu Z-Z 2015 *Carbon* **82** 67
[121] Chen Y-J, Dung N D, Li Y-A, Yip M-C, Hsu W-K and Tai N-H 2011 *Diam. Rel. Mater.* **20** 1183
[122] Singh K, Ohlan A, Pham V H, Balasubramaniyan R, Varshney S, Jang J *et al* 2013 *Nanoscale* **5** 2411